Cone Angle Choices For Atmospheric Entry Vehicles: A Review

Michael Tauber
ELORET Corp.
NASA-Ames Research Center

Michael Wright
Kerry Trumble
Reacting Flow Environments Branch
NASA-Ames Research Center

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Why Do Cone Angles Of Entry Probes And Landers Vary from 45^o To 70^o?

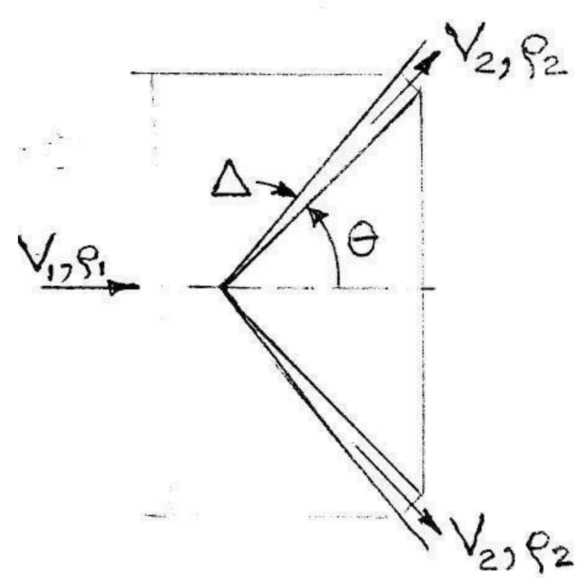
- Parameters that affect cone angle choices - packaging, atmosphere, heating, stability, etc.
  - Advantages of 45^o cone angle
    - Packing of pressure vessels
    - Can decrease heating rates
    - High-speed dynamic stability
  - Larger cone angles
    - Decrease entry heating duration
    - Can increase heating rate, especially radiation
    - Increase descent heat conduction
    - Can decrease dynamic stability

- The thin conical shock layer, $\Delta << \Theta$, sharp nose, $\alpha=0$, $\varepsilon=\rho_1/\rho_2<<1$

$$\frac{V_2}{V_1} = (1 - \Delta \tan\theta)\cos\theta$$

$$2\Delta^2 \tan\theta - (2-\varepsilon)\Delta + \varepsilon \tan\theta = 0$$

$$\theta_{max} = \tan^{-1}\left(\frac{2-\varepsilon}{2\sqrt{2\varepsilon}}\right)$$



- Aerodynamic stability, $\alpha << \Theta$

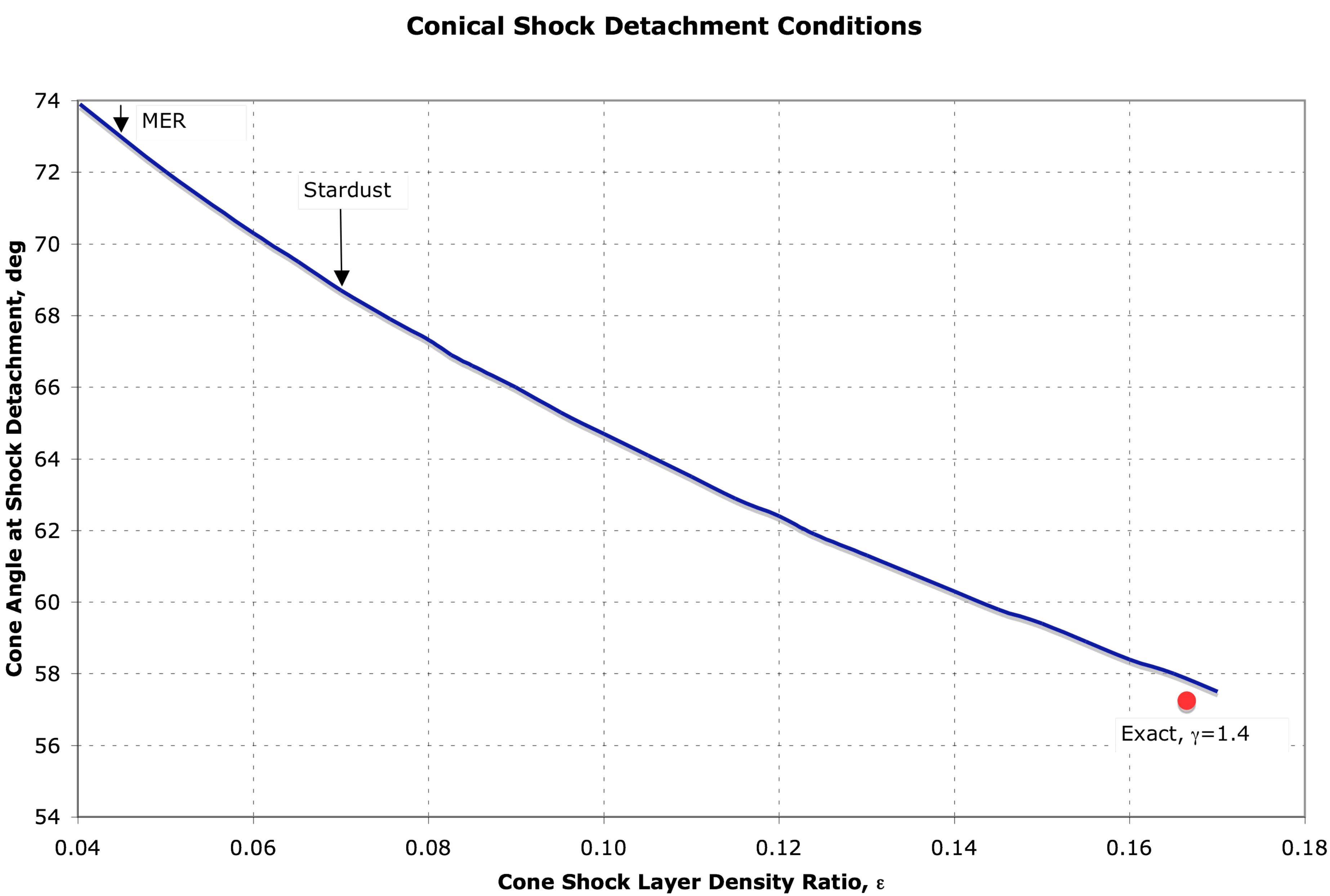
$$C_L = 2(\cos^2\theta - \sin^2\theta)\alpha$$

$$\rightarrow \text{at } \theta = 45^o, \ \frac{dC_L}{d\alpha} = 0$$

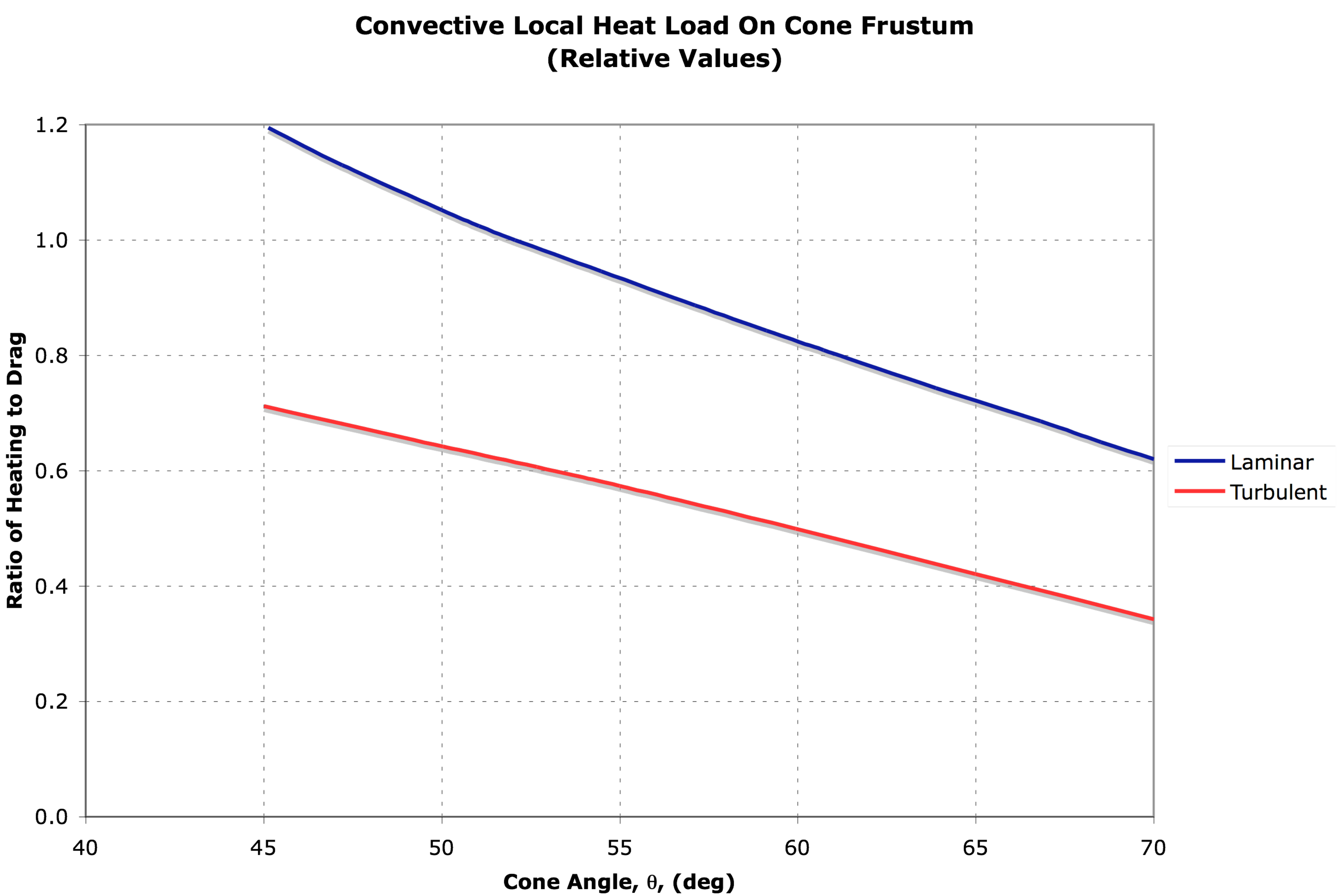
- Entry trajectory and heating
  - Boundary layer; lam n=0.5, turb n=0.8
  - Radiation; inner planets n=1.19-1.22
  - Radiation; outer planets n=1.17-1.45

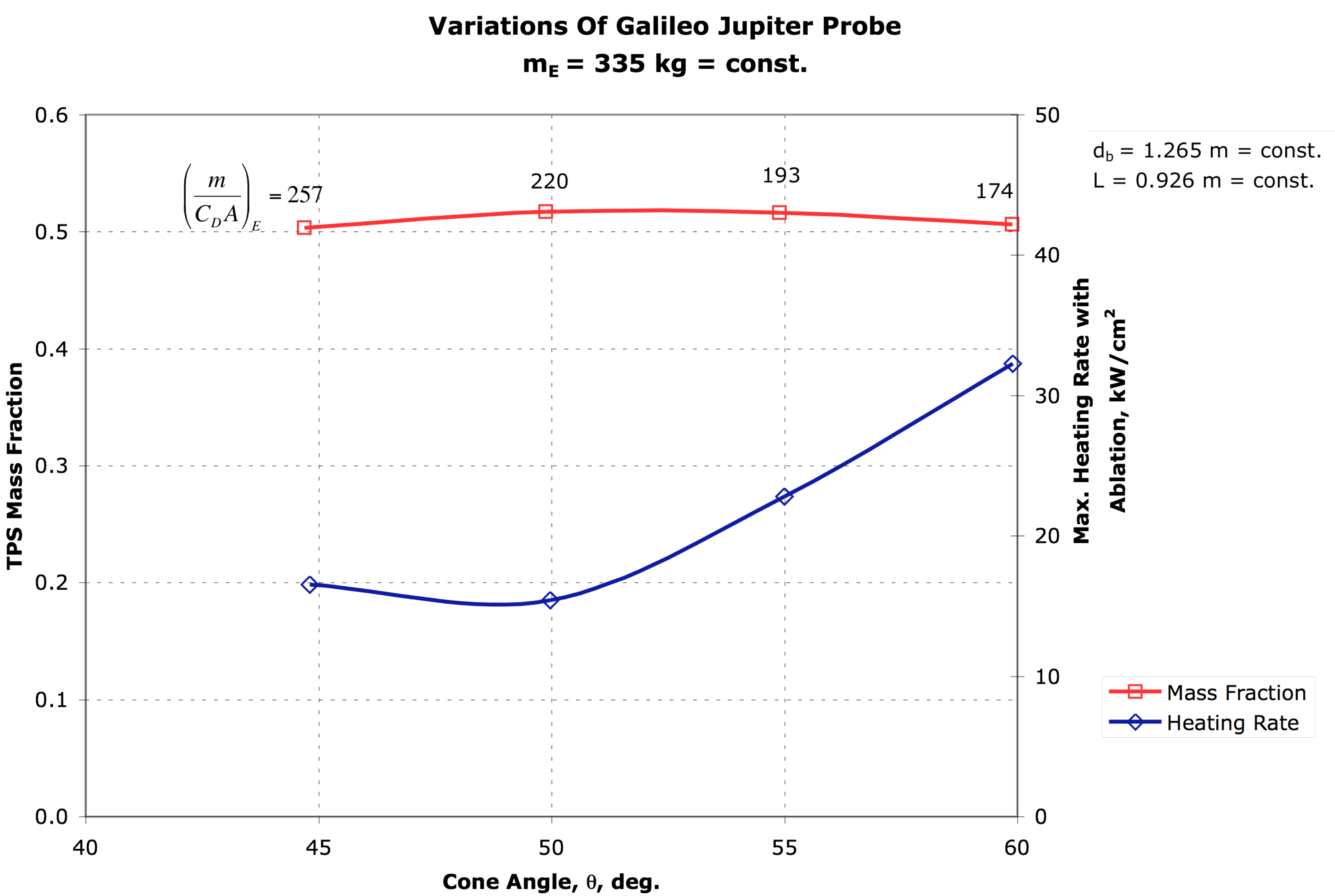
$$-\frac{dV}{dt} = \frac{D}{m} = \frac{1}{2\rho_1 V_1^2}\left(\frac{C_D A}{m}\right) \text{ and } \frac{dq}{dt} \sim \rho_1^n V_1^m$$

$$\rightarrow \text{heat load } q \sim \left(\frac{m}{C_D A}\right)^n$$



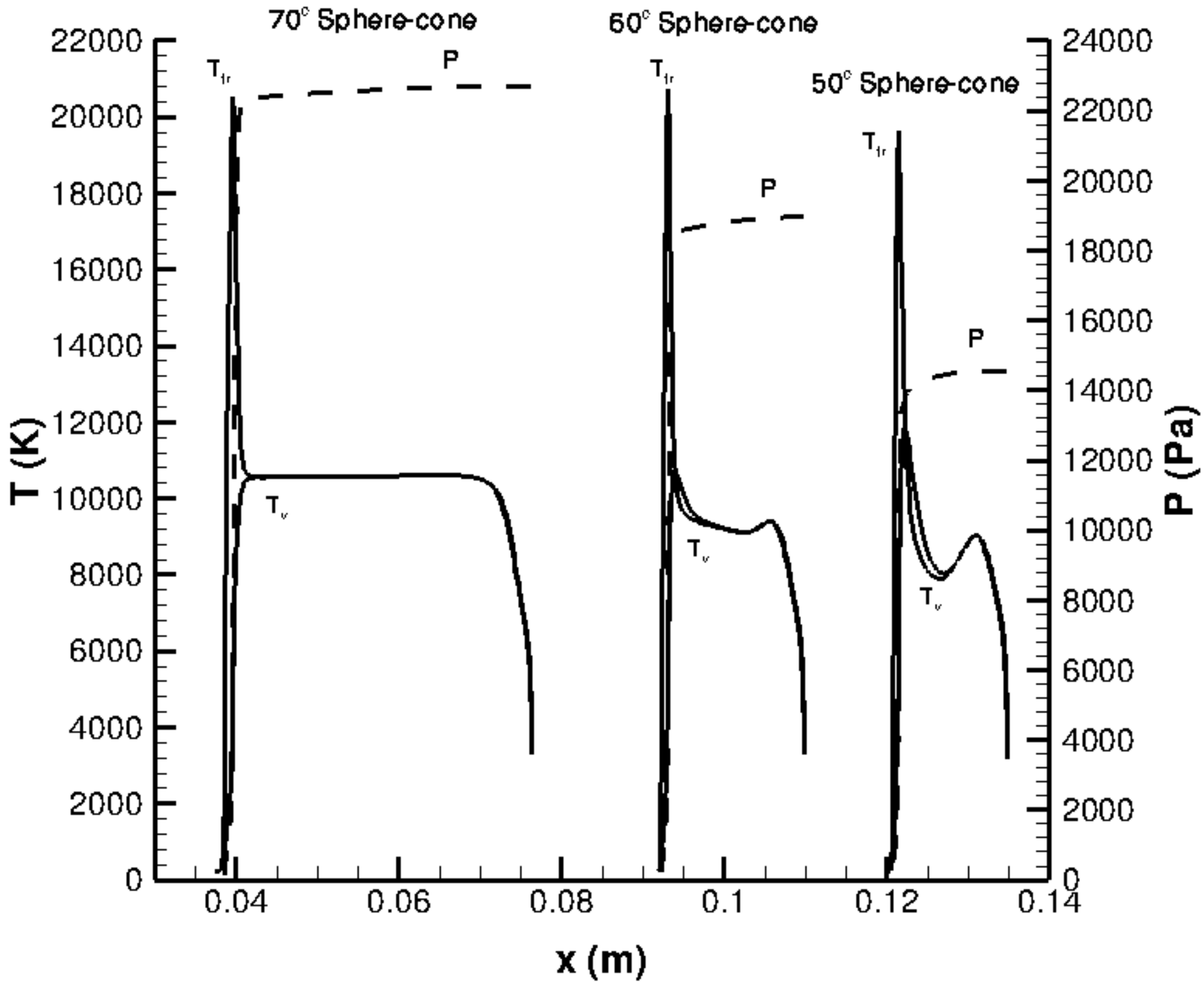
Conical Shock Detachment Conditions
Cone Angle at Shock Detachment, deg
Cone Shock Layer Density Ratio, ε
MER
Stardust
Exact, γ=1.4
74
72
70
68
66
64
62
60
58
56
54
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18


Convective Local Heat Load On Cone Frustum
(Relative Values)
Ratio of Heating to Drag
Cone Angle, θ, (deg)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
40
45
50
55
60
65
70
Laminar
Turbulent



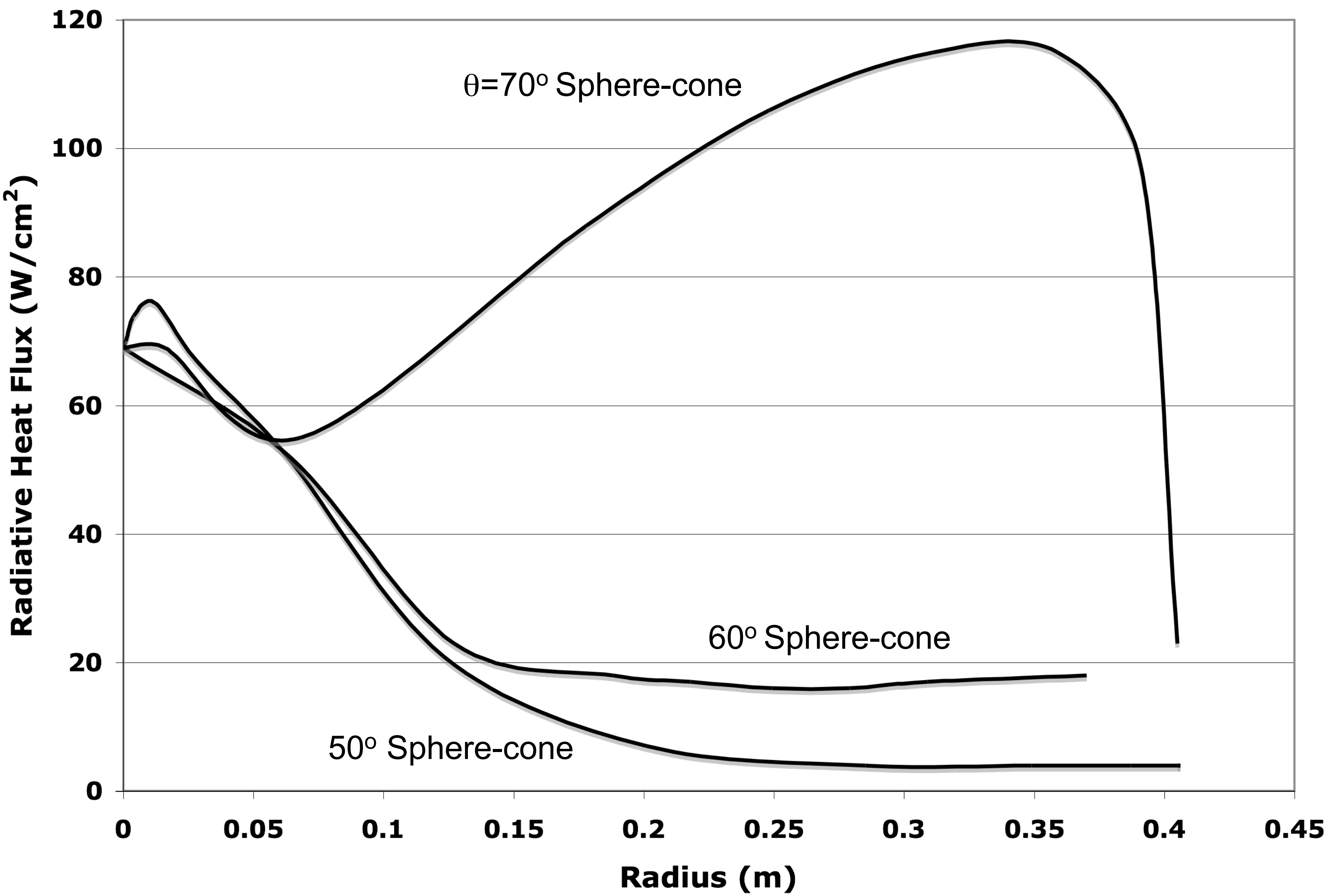
Variations Of Galileo Jupiter Probe
m_E = 335 kg = const.
d_b = 1.265 m = const.
L = 0.926 m = const.
$\left(\frac{m}{C_D A}\right)_E = 257$
220
193
174
TPS Mass Fraction
Max. Heating Rate with Ablation, kW/cm^2
Cone Angle, θ, deg.
Mass Fraction
Heating Rate
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
40
45
50
55
60

Shock Layer Temperature and Pressure Distributions at Cone Frustum Midpoints



V = 10.871 km/s, altitude = 61.761 km

Variations of Stardust Capsule



Heat Conduction During Descent

- Simplifying assumptions: terminal descent, exponential atm. density variation with altitude

$$mg\sin\gamma = D = \frac{1}{2}\rho V^2 C_D A$$

Since $\sin\gamma \to 1$ and $\rho \sim e^{-y/\eta}$, where η is atm. density scale height

$$dt = \frac{\eta}{\rho V}d\rho$$

Now the approximate descent time, t_d, becomes

$$t_d \sim \left(\frac{m}{C_D A}\right)^{-1/2}\left(\frac{\rho_o}{g}\right)^{1/2}\eta$$

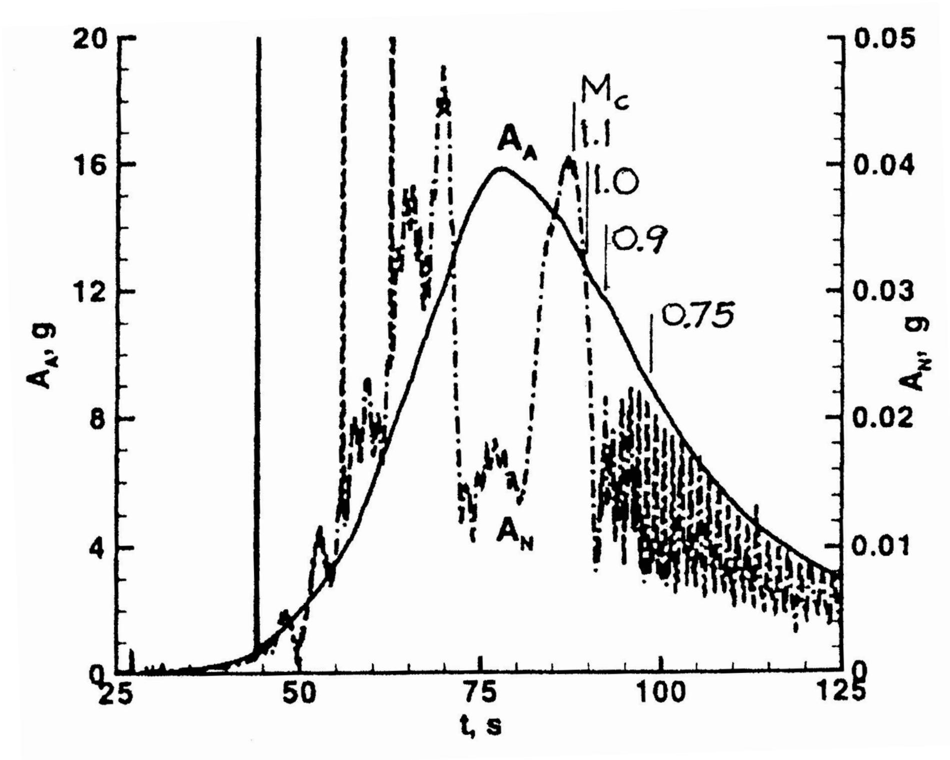
Where ρ_o is the atm. density where heat shield is discarded

- Note that heat conduction time is reduced by decreasing the C_D, or cone angle. In contrast, during entry the heat load is decreased by increasing the C_D, or cone angle

$$q \sim \left(\frac{m}{C_D A}\right)^n \text{ where } n > 0$$

- Also, note the effect of atm. density, ρ_o, and scale height, η, on the descent time

Mars Pathfinder Entry Dynamics

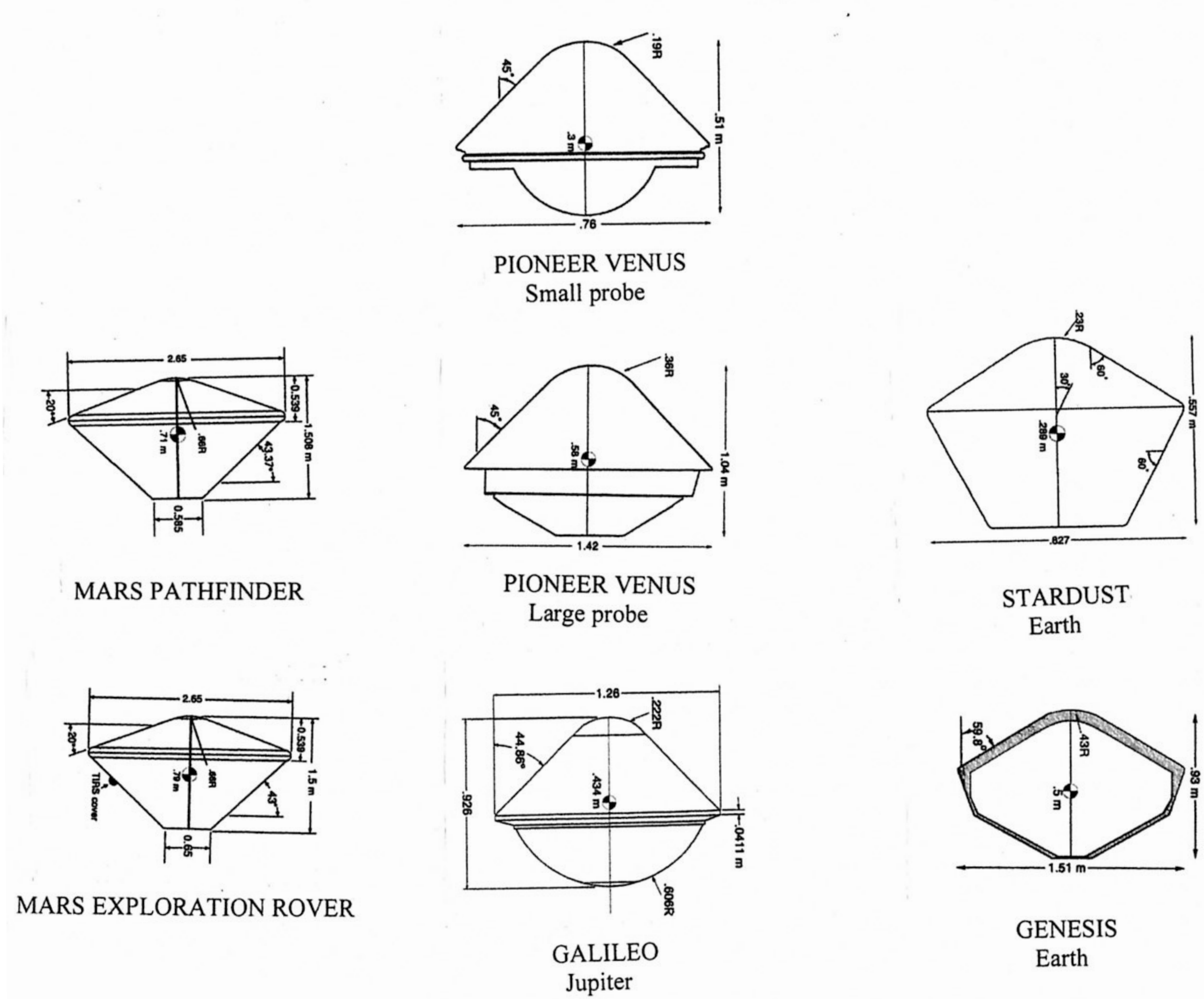


Total off-axis acceleration recorded during 100-s interval surrounding peak dynamic pressure.

$$M_C = \frac{(\cot\theta)(1 - \frac{\varepsilon \tan^2\theta}{2-\varepsilon})}{\sqrt{\gamma\varepsilon}}$$

Gnoffo, et al, “Prediction and Validation of Mars Pathfinder Hypersonic Aerodynamics Database,” *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 367-373

PLANETARY ATMOSPHERE ENTRY PROBE CONFIGURATIONS

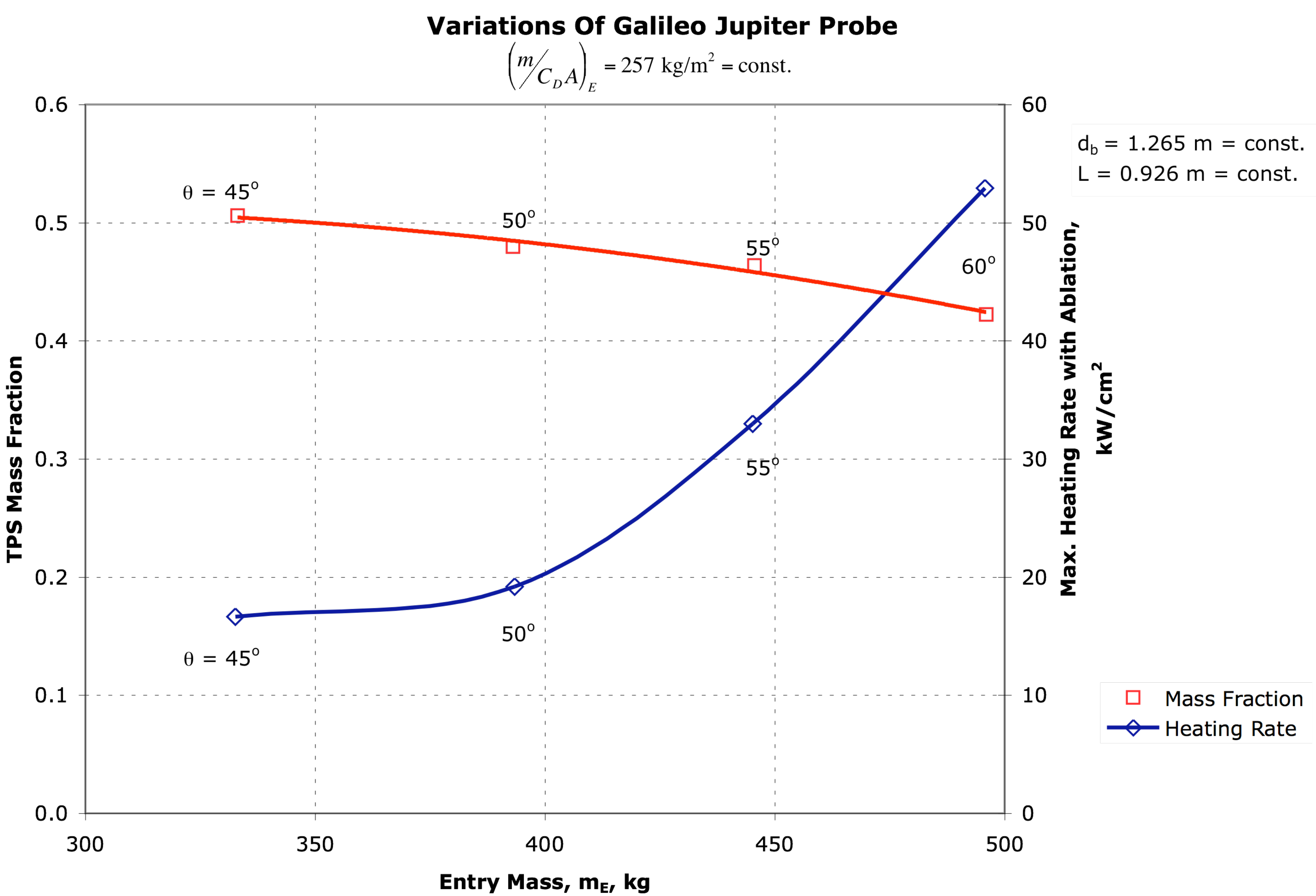


Davies, C., “Planetary Mission Entry Vehicles”, Version 2.1, NASA Ames Research Center

Conclusions

Cone Angle	Planet(s)	V_E km/s	Atm.	Press. Vessel	Max. Heating w/o Ablat. kW/cm2	Rel. Time	C_D
70^o	Mars	6-7	Thin triatom.	no	Low (~0.1)	short	1.7
60^o	Earth	11-13	Med. Diatom.	no	Med (~1.0)	Med.	1.5
45^o	Venus	11-12	Dense triatom.	yes	High (~5.0)	Very long	1.0
45^o	Jupiter	48	Med. Diatom.	yes	Severe (~50.0)	long	1.0
45^o	Other outer planets	25-30	Med. Diatom.	yes	High (~5.0)	Very long - long	1.0

Back-up Slides



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TPS Mass Fraction
Max. Heating Rate with Ablation, kW/cm^2
Entry Mass, m_E, kg
θ = 45°
50°
55°
60°
Mass Fraction
Heating Rate
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
60
300
350
400
450
500